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PAPER

Analog Decoding Method for Simplified Short-Range MIMO Transmission

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SUMMARY A novel analog decoding method using only 90-degree phase shifters is proposed to simplify the decoding method for short-range multiple-input multiple-output (MIMO) transmission. In a short-range MIMO transmission, an *optimal element spacing* that maximizes the channel capacity exists for a given transmit distance between the transmitter and receiver. We focus on the fact that the weight matrix by zero forcing (ZF) at the optimal element spacing can be obtained by using dividers and 90-degree phase shifters because it can be expressed by a unitary matrix. The channel capacity by the proposed method is next derived for the evaluation of the exact limitation of the channel capacity. Moreover, it is shown that an optimal weight when using directional antennas can be expressed by using only dividers, 90-degree phase shifters, and attenuators, regardless of the beam width of the directional antenna. Finally, bit error rate and channel capacity evaluations by both simulation and measurement confirm the effectiveness of the proposed method.
key words: *short-range MIMO transmission, zero forcing, unitary matrix, 90-degree phase shifter, optimal element spacing*

1. Introduction

Because of the recent popularity of smartphones and wireless local area network (WLAN), ultimate high-speed data communication at speeds over 10 Gbps is essential in future wireless communication systems [1]–[3]. Multiple-input-multiple-output (MIMO) systems have attracted significant attention because they can improve the transmission rate within a limited frequency band [4], [5]. Moreover, they have already been commercialized in latest cellular and WLAN systems [6], [7].

Multipath-rich environments are generally considered for MIMO systems, and independent and identically distributed (i.i.d.) channels are usually assumed to explain such environments in a simple manner [4], [5]. Paulaj et al. indicated that the channel capacity in a specific channel exceeds the ergodic capacity of an i.i.d. channel, even when the Rician factor is infinite [5]. Recently, the existence of optimal element spacing has been confirmed such that the channel capacity is maximized for a given signal-to-noise power ratio (SNR), even when a line-of-sight (LOS) environment is considered [8]–[10]. The relationship between the optimal element spacing and transmit distance is theoretically derived in the closed form when considering the linear array [9] and rectangular array [10]. However, there is an issue on complexity of signal processing in the conventional MIMO system.

Short-range communications have been also attracted much attention [11]–[13], because they can realize the very high speed communication by using broadband signals. For ultimate high-speed data communication at speeds over 10 Gbps, the combination of MIMO transmission and short-range communication is effective. This concept is called short range MIMO (SR-MIMO) [14] and it is clarified that the concept of LOS-MIMO can be applicable in SR-MIMO [15].

As concrete applications on SR-MIMO transmission, there are wireless repeater which connects networks through a wall [15] and communication between chips [16], and so on. Although very high-speed communication is required in such applications, the variation on the propagation channel is assumed to be very small: The static propagation environment is realized. Hence, weights by obtained MIMO transmission or decoding method can be fixed and conventional MIMO signal processing is not required when considering the burden on signal processing part. Although there are studies regarding SR-MIMO transmission [17]–[20], the simplification on signal processing part have not been evaluated in [17]–[20].

It was clarified that the channel capacity when using Zero Forcing (ZF) [21] is the same as that using Eigenmode-beamforming (EM-BF) [22], [23] when considering the optimal element spacing in the SR-MIMO [24]. However, the computational complexity of the ZF method is still large because the calculation of channel inversion is required in the ZF method.

We proposed the decoding method using a simple analog circuit to simplify the decoding method in an SR-MIMO transmission [25]. This method utilizes the fact that the channel matrix becomes a unitary matrix by properly adjusting the phase differences among transmit and receive antennas with optimal element spacing. The weights produced by ZF with optimal element spacing are approximated by using 90-degree phase shifters and dividers. This circuit realizes MIMO decoding that has the same ability as the ZF method

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without any digital signal processing. By the evaluation of the bit error rate, it was found that BER by the proposed method is not degraded compared to the ZF method when considering the optimal element spacing.

This manuscript contains a significantly broadened treatment of the proposed approach. In particular:

- The optimal condition in SR-MIMO transmission is described in greater detail. The relationship among eigenvalues, spatial correlation, and the unitary condition is explained in Sect. 2.
- We theoretically derive the channel capacity when considering the simple decoding method. Although only BER evaluation is employed in [25], the theoretical upper bound by the proposed method is evaluated via the channel capacity evaluation.
- Because planar arrays between the transmitters and receivers should face each other for short-range communication, the use of a directional antenna such as a microstrip antenna (MSA) is essential. In this paper, the optimal weight when considering the directional antennas is derived.
- We investigate the measurements to verify the effectiveness of our theory. Moreover, frequency characteristics, which are a very important factor in broadband communications, are also evaluated.

The remainder of this paper is organized as follows. Section 2 shows the optimal weight for SR-MIMO. It is shown that this condition can be derived by the unitary matrix that is obtained from the antenna arrangement with optimal element spacing. A configuration that realizes a simple decoding method using analog devices is proposed in Sect. 3. In Sect. 3, the channel capacity of the simple decoding method is derived, and the optimal condition when using a directional antenna is exhibited. Section 4 evaluates the channel capacity and BER performance in order to show the effectiveness of the proposed analog decoding method. The experimental results by the proposed method are shown in Sect. 5 to show the validity of our theory and simulation results.

2. Weight and Channel Matrices for Optimal Element Spacing in SR-MIMO

2.1 Optimal Element Spacing in SR-MIMO

We consider the channel capacity versus array element spacing, d, to show the optimal condition in SR-MIMO. The simulation condition is shown hereafter. The transmit distance between transmit and receive antennas is set to be $D = 2\lambda_0$. Here, λ_0 denotes the wavelength of the transmitted signal. Two identical array antennas that face each other, each of which is a dipole array with a spacing of d, are placed parallel to each other and separated by D. All antennas have vertical polarization for simplicity. The SNR per antenna is 20 dB. The simulation considers the free space between the array antennas. In this simulation, we adopt the geometrical optics approximation for the propagation channel in the SR-MIMO.

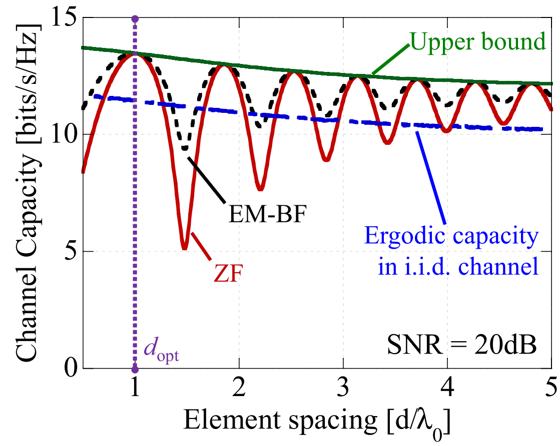

Fig. 1 Channel capacity versus element spacing (2×2 MIMO, $D = 2\lambda_0$).

Figure 1 shows the channel capacity versus element spacing, d. Ergodic channel capacity in the i.i.d. channel and the upper bound, at which all the eigenvalues with the given SNR are identical, are plotted in this figure. As can be seen in Fig. 1, the channel capacity by using EM-BF / ZF is identical to that of the upper bound when $d = 1.0\ \lambda_0$. This result confirms the existence of the optimal element spacing, d_{opt}, when the EM-BF and ZF is adopted [24]. It can be also seen that the capacity with d_{opt} by using EM-BF or ZF is higher than the ergodic capacity in the i.i.d. channel, which is commonly used as the channel model in conventional MIMO transmission. Moreover, the channel capacity using ZF is almost the same as that using EM-BF, when considering d_{opt}.

It is shown that the maximum value of the channel capacity is small when the transmit distance, D, is increased [24]. In addition, the optimal element spacing, d_{opt}, is changed when D is given, and the value of d_{opt} is wider when D is increased [24].

2.2 Zero Forcing Algorithm

The ZF method is well known as a simple decoding algorithm in a MIMO system because only receivers employ signal processing, unlike EM-BF. The weight matrix, $\boldsymbol{W_{ZF}}$, is calculated by using the channel inversion, which is obtained by channel estimation at the receivers in the ZF algorithm. Our aim is to realize the simple decoding method, as the computational complexity by the ZF algorithm is still large because of the calculation of the channel inversion. As shown in Fig. 1, the channel capacity using ZF is almost the same as that using EM-BF, when considering d_{opt} in the SR-MIMO system. We focus on the condition of the weight matrix, $\boldsymbol{W_{ZF}}$, which is obtained by the ZF algorithm. We realize a fixed weight, $\boldsymbol{W_S}$, that can be configured by an analog circuit. The detailed scheme is shown in Sect. 3.

Here, the basic principle of ZF is described. When $\boldsymbol{H_0}$ is the weight matrix for the channel, $\boldsymbol{H_0}$ with an $M \times$

M MIMO channel is denoted as

$$\boldsymbol{H_0} = \begin{bmatrix} h_{11} & h_{12} & \cdots & h_{1M} \\ h_{21} & h_{22} & \cdots & h_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ h_{M1} & h_{M2} & \cdots & h_{MM} \end{bmatrix}, \quad (1)$$

where h_{ij} is the channel response for the j-th and i-th transmit and receive antennas. The receive signal vector, $\boldsymbol{y}(t) = [y_1(t), \cdots, y_M(t)]^T$ is denoted as

$$\boldsymbol{y}(t) = \boldsymbol{H_0}\boldsymbol{s}(t) + \boldsymbol{n}(t), \quad (2)$$

where $\boldsymbol{s}(t) = [s_1(t) \cdots, s_M(t)]^T$ and $\boldsymbol{n}(t) = [n_1(t), \cdots, n_M(t)]^T$ denote the receive signal and noise vectors, respectively. Here, T is the transpose operation on the vector.

The weight matrix of ZF, $\boldsymbol{W_{ZF}}$, is represented as

$$\boldsymbol{W_{ZF}} = \boldsymbol{H_0}^{-1}. \quad (3)$$

Hence, the decoding signal vector, $\boldsymbol{y'}(t)$, is denoted as

$$\begin{aligned} \boldsymbol{y'}(t) &= \boldsymbol{W_{ZF}}\boldsymbol{y}(t) \\ &= \boldsymbol{W_{ZF}}\boldsymbol{H_0}\boldsymbol{s}(t) + \boldsymbol{W_{ZF}}\boldsymbol{n}(t). \end{aligned} \quad (4)$$

In the next subsection, we analyze how the elements of $\boldsymbol{W_{ZF}}$ are changed when changing the element spacing in the SR-MIMO system.

2.3 Weight of ZF with Optimal Element Spacing

For the following explanation, the element spacings that firstly and secondly maximize the channel capacity in Fig. 1 are defined as $d_{\mathrm{opt},1}$ and $d_{\mathrm{opt},2}$, respectively. In order to examine the characteristics of $\boldsymbol{W_{ZF}}$, $\boldsymbol{W_{ZF}}$ is normalized by w_{11} as

$$\frac{\boldsymbol{W_{ZF}}}{w_{11}} = \begin{bmatrix} w_{11}/w_{11} & w_{12}/w_{11} \\ w_{21}/w_{11} & w_{22}/w_{11} \end{bmatrix}, \quad (5)$$

where $w_{22} = w_{11}$, and $w_{12} = w_{21}$ because of the symmetric property of the array configuration. We focus on the weight matrix created by ZF when $d = d_{\mathrm{opt},1}$ in Fig. 1. When $d_{\mathrm{opt},1}$ is given, $\boldsymbol{W_{ZF}}/w_{11}$ is calculated as

$$\frac{\boldsymbol{W_{ZF}}}{w_{11}} = \begin{bmatrix} 1 & -0.04 + 0.89j \\ -0.04 + 0.89j & 1 \end{bmatrix}. \quad (6)$$

As shown in Eq. (6), the ratio of $|w_{21}/w_{11}|$ ($|w_{12}/w_{22}|$) is 0.91, and $\tan^{-1}(w_{21}/w_{11})$ ($\tan^{-1}(w_{12}/w_{22})$) is approximately 90 degrees. Note that this condition in the optimal element spacing is constant even if the transmit distance, D, is changed.

Figure 2 shows the amplitude ratio ($|w_{11}/w_{21}|$) versus the element spacing when using the ZF algorithm. As can be seen in Fig. 2, the amplitude ratio when $d = d_{\mathrm{opt},1}$ is approximately 1.1, and the amplitude ratio increases in proportion to the element spacing, d.

Figure 3 denotes the phase difference, θ_W ($\tan^{-1}$ (w_{11}/w_{21})), versus the element spacing when using the ZF algorithm. As can be seen in Fig. 3, θ_W at the element spacing that maximizes the channel capacity in Fig. 1 is expressed as

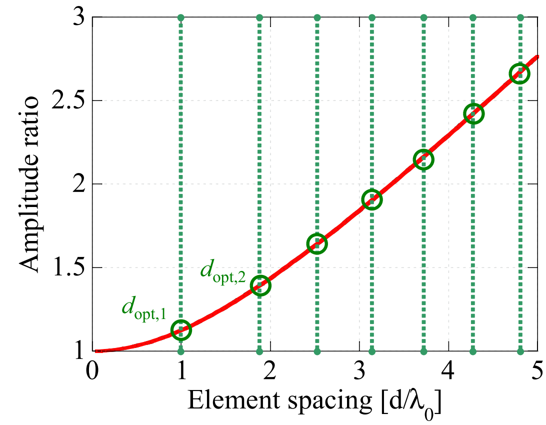

Fig. 2 Amplitude ratio versus array element spacing.

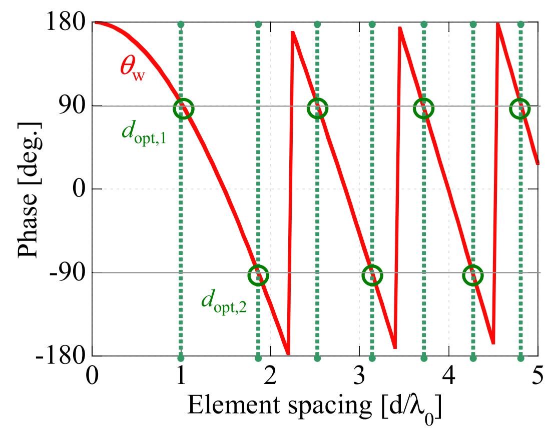

Fig. 3 Phase difference versus array element spacing.

$$\begin{cases} \theta_W(d_{\mathrm{opt},1}) = \ldots = \theta_W(d_{\mathrm{opt},2n+1}) \cong 90^\circ \\ \theta_W(d_{\mathrm{opt},2}) = \ldots = \theta_W(d_{\mathrm{opt},2n}) \cong -90^\circ \end{cases} \quad (7)$$

Hence, $\boldsymbol{W_{ZF}}$ and channel matrix $\boldsymbol{H_0}$ when considering $d_{\mathrm{opt},1}$ can be approximated by

$$\frac{\boldsymbol{W_{ZF}}}{w_{11}} \cong \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix}, \quad (8)$$

$$\frac{\boldsymbol{H_0}}{h_{11}} \cong \begin{bmatrix} 1 & -j \\ -j & 1 \end{bmatrix}. \quad (9)$$

When considering the above condition, the following relationship is obtained.

$$\boldsymbol{W_{ZF}} = \boldsymbol{H_0}^{-1} = \boldsymbol{H_0}^H. \quad (10)$$

As a result, it is shown that the weight matrix of ZF can be approximated by a unitary matrix when considering the optimal element spacing in the SR-MIMO system.

2.4 Channel Matrices and Unitary Matrix for Optimal Element Spacing

Let us assume a unitary matrix, $\boldsymbol{U}$. A unitary matrix has the following property:

$$\boldsymbol{U}\boldsymbol{U}^H = \boldsymbol{U}^H\boldsymbol{U} = \boldsymbol{I}, \tag{11}$$

where $\boldsymbol{I}$ is the identity matrix. Hence, $\boldsymbol{U}^H = \boldsymbol{U}^{-1}$ [26]. As shown in the previous subsection, $\boldsymbol{W_{ZF}}$ and $\boldsymbol{H_0}$ are approximated by the unitary matrix. Hence, $\boldsymbol{W_{ZF}}\boldsymbol{H_0}$, which is the channel matrix after multiplying the weight matrix, is denoted as

$$\boldsymbol{W_{ZF}}\boldsymbol{H_0} = \boldsymbol{H_0}^{-1}\boldsymbol{H_0} = \boldsymbol{H_0}^H\boldsymbol{H_0} = \boldsymbol{I}. \tag{12}$$

When considering the above condition, all the eigenvalues are identical, and the spatial correlation is zero [24]. This is an optimal condition in MIMO transmission: the maximum channel capacity is obtained for the given SNR.

3. Analog Beamforming Circuit Using Condition on Optimal Element Spacing

3.1 Analog Beamforming Circuit

As mentioned in 2.3, $\boldsymbol{W_{ZF}}/w_{11}$ in a 2×2 MIMO system considering the optimal element spacing can be approximated by

$$\frac{\boldsymbol{W}}{w_{11}} \cong \begin{bmatrix} 1 & j \\ j & 1 \end{bmatrix} \cong \frac{\boldsymbol{H_0}^H}{h_{11}^H}. \tag{13}$$

We propose an analog decoding method by utilizing the fact that the propagation channel is not changed in the SR-MIMO when Eq. (13) is obtained. The condition in Eq. (13) can be configured by using only *simple analog devices* with dividers and 90-degree phase shifters. Figure 4 shows the proposed analog beamforming circuit. As shown in Fig. 4, because two pairs of weights can be multiplied with the received signals, the inter-steam interference can be automatically canceled at the output signals, $y_1^{'}$ and $y_2^{'}$: MIMO transmission is realized without any decoding scheme such as channel inversion in the digital signal processor.

The decoding signal vector $\boldsymbol{y'}(t)$ using analog weight $\boldsymbol{W_s}$ is denoted as

$$\begin{aligned}\boldsymbol{y'}(t) &= \boldsymbol{W_s}\boldsymbol{H_0}\boldsymbol{s}(t) + \boldsymbol{W_s}\boldsymbol{n} \\ &\propto \boldsymbol{R}\boldsymbol{s}(t) + \boldsymbol{W_s}\boldsymbol{n}(t).\end{aligned} \tag{14}$$

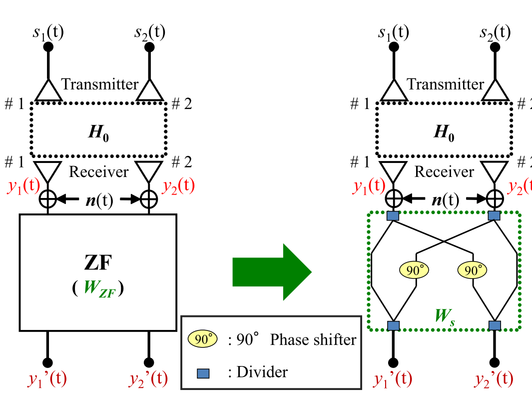

Fig. 4 Proposed analog beamforming circuit.

When an $M \times M$ MIMO channel is considered for $\boldsymbol{R}$ in Eq. (14), $\boldsymbol{R}$ is expressed as

$$\boldsymbol{R} = \begin{bmatrix} a_{11} & a_{12} & \cdots & a_{1M} \\ a_{21} & a_{22} & \cdots & a_{2M} \\ \vdots & \vdots & \ddots & \vdots \\ a_{M1} & a_{M2} & \cdots & a_{MM} \end{bmatrix}. \tag{15}$$

Because $\boldsymbol{W_s}$ with 2×2 MIMO is the unitary matrix, $\boldsymbol{R}$ in Eq. (14) is approximated as

$$\frac{\boldsymbol{R}}{a_{11}} = \begin{bmatrix} 1 & 0 \\ 0 & 1 \end{bmatrix} = \boldsymbol{I}. \tag{16}$$

Hence, the inter-stream interference can be canceled, and the desired signals can be decoded by the proposed circuit.

Although the proposed decoding in a 2×2 MIMO system can be realized by using the circuit in Fig. 4, the idea for the proposed method can be applicable for a larger number of antennas. Let us assume a 4×4 MIMO system with squarely arranged antennas at the transmitter and receiver. Figure 5 shows the 4×4 MIMO system with squarely arranged antennas at the transmitter and receiver. When considering this antenna arrangement, $\boldsymbol{W_{ZF}}(a,b)/w_{11}$ $(a,b = 1 \sim 4)$ can be calculated as

$$\boldsymbol{W_{ZF}}(k,k)/w_{11} = 1 \quad (k = 1 \sim 4) \tag{17}$$

$$\boldsymbol{W_{ZF}}(i,j)/w_{11} = -0.09 + 0.89j \quad (i = 2,3,\ j = 1,4) \tag{18}$$

$$\boldsymbol{W_{ZF}}(m,n)/w_{11} = -0.09 + 0.89j \quad (m = 1,4,\ n = 2,3) \tag{19}$$

$$\boldsymbol{W_{ZF}}(5-l,l)/w_{11} = -0.78 - 0.04j \quad (l = 1 \sim 4). \tag{20}$$

We approximate the above matrix to realize a simple decoding method with an analog circuit that uses only dividers and 90 and 180-degree phase shifters. The approximated matrix, $\boldsymbol{W_{s,4\times4}}$, is expressed as

$$\boldsymbol{W_{s,4\times4}} = \begin{bmatrix} 1 & j & j & -1 \\ j & 1 & -1 & j \\ j & -1 & 1 & j \\ -1 & j & j & 1 \end{bmatrix}, \tag{21}$$

where $\boldsymbol{W_s}$ is the unitary matrix because $\boldsymbol{W_{s,4\times4}}\boldsymbol{W_{s,4\times4}}^H$ is the

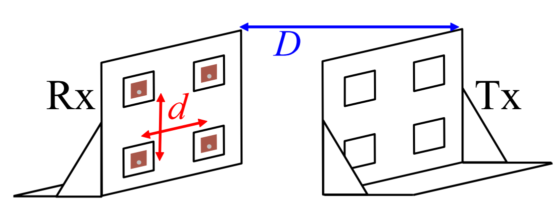

Fig. 5 4×4 MIMO system with squarely arranged antennas at the transmitter and receiver.

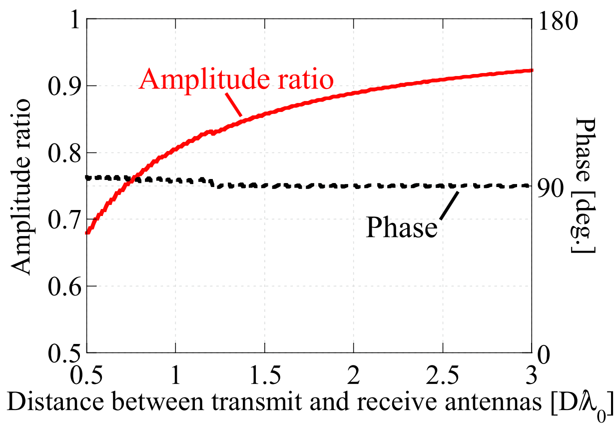

Fig. 6 Amplitude ratio and phase difference at the optimal element spacing of each D.

identity matrix.

Although the optimal element spacing itself is changed when the transmit distance, D, is changed, the weight for the simple decoding method is not changed. Figure 6 shows the amplitude ratio and phase difference of $\boldsymbol{W_{ZF}}$ at the optimal element spacing when D is changed. As can be seen in Fig. 6, the amplitude ratio is increased when D is wider. The adjustment of amplitude can be used by the attenuator. Furthermore, the phase difference is approximately 90° as a 90-degree phase shifter is used. Hence, the simple decoding method can be realized by the analog weight circuit with the optimal element spacing when D is determined.

3.2 Derivation of Channel Capacity

The performance by the proposed method is degraded because the approximation of the weights by using the unitary condition is adopted. In this subsection, the channel capacity by the proposed method is derived in an exact expression to accurately evaluate the upper bound of the channel capacity by the proposed method.

Here, we introduce a new parameter, b_{ki} $(k = 1 \sim M, i = 1 \sim M, i \neq k)$. b_{ki} is defined as

$$b_{ki} = \frac{a_{ki}}{a_{kk}} (k = 1 \sim M, i = 1 \sim M, i \neq k). \tag{22}$$

$|b_{ki}|$ is approximated by 0 at the optimal element spacing. On the other hand, $|b_{ki}|$ is large when the channel capacity is low. Hence, b_{ki} can be treated as the influence of the inter-steam interference. Thus, the signal-to-interference-and-noise power ratio (SINR) for the k-th received antenna by the proposed method is denoted as

$$SINR(k) = \frac{E\lfloor |s_k(t)|^2 \rfloor}{\sum_{i \neq k, i=1}^{M} |b_{ki}|^2 E\lfloor |s_i(t)|^2 \rfloor + E\lfloor |n_k(t)|^2 \rfloor}. \tag{23}$$

Here, $E\lfloor\cdot\rfloor$ is expectation value. Hence, the channel capacity, C, using the proposed method is expressed as

$$C = \sum_{k=1}^{M} \log_2 \left(1 + \frac{1}{M} SINR(k)\right). \tag{24}$$

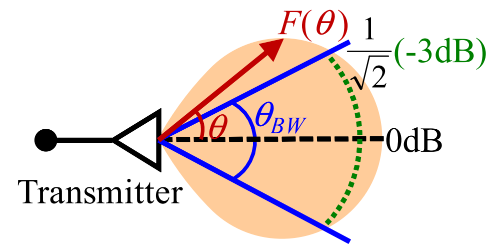

Fig. 7 Schematic of the effect of the radiation pattern and the antenna directivity.

3.3 Analog Weight for Directional Antenna

Figure 7 shows the definition of the 3-dB beamwidth (BW) when using a directional antenna. θ_{BW} is the half-power beamwidth (HPBW). The antenna pattern from the directional antenna is generally approximated by $\cos^n$ (n: positive value). Hence, the response of the directional antenna in the direction of θ, $F_{\theta_{BW}}(\theta)$ is expressed as

$$F_{\theta_{BW}}(\theta) = \cos^n(\theta). \tag{25}$$

Here, n is calculated by θ_{BW} as

$$\cos^n\left(\frac{\theta_{BW}}{2}\right) = \frac{1}{\sqrt{2}} \tag{26}$$

$$n = -\frac{1}{2\log_2\{\cos\left(\frac{\theta_{BW}}{2}\right)\}}. \tag{27}$$

When using the directional antennas, $\boldsymbol{W_{ZF}}/w_{11}$ in 2×2 SR-MIMO with the optimal element spacing can be approximated by

$$\frac{\boldsymbol{W}}{w_{11}} \cong \begin{bmatrix} 1 & j\alpha \\ j\alpha & 1 \end{bmatrix} \cong \frac{\boldsymbol{H_0}^H}{h_{11}^H}, \tag{28}$$

where we define α as the weight factor. Figure 8 shows the characteristics of α and the phase difference, $\tan^{-1}(w_{21}/w_{11})$ or $\tan^{-1}(w_{12}/w_{22})$, at the optimal element spacing when D is changed. Here, the HPBW is set to be 80 degrees. As shown in Fig. 8, α is increased when D is wider, but α is saturated. On the other hand, it is shown that the phase difference is approximately 90 degrees.

Figure 9 shows the characteristics of α and the phase difference, $\tan^{-1}(w_{21}/w_{11})$ or $\tan^{-1}(w_{12}/w_{22})$, at the optimal element spacing when the HPBW is changed. D is set to be $5\lambda_0$. As can be seen in Fig. 9, α is increased when the HPBW is wider, but α is saturated. Hence, an attenuator is required to realize the weights with the analog circuit. On the other hand, the phase difference is approximately 90 degrees, regardless of the HPBW.

From the results in Figs. 8 and 9, it was found that the analog weight can be realized by using a divider, 90-degree phase shifter, and attenuator when using the directional antennas. Figure 10 shows the proposed analog beamforming circuit when using the directional antenna. The condition in Eq. (28) can be configured by using only *simple analog devices* with dividers, 90-degree phase shifters, and attenuators.

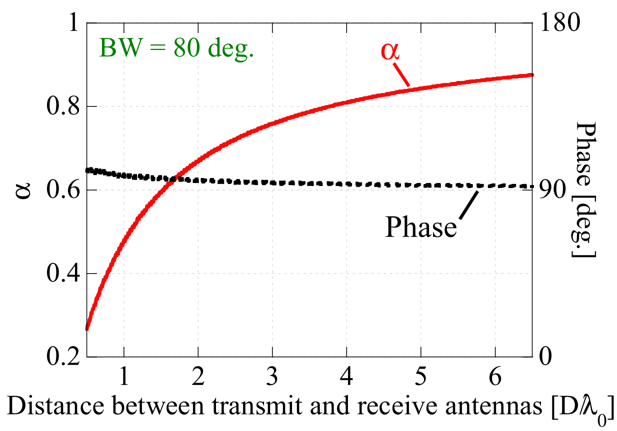

Fig. 8 Weight factor α and the phase difference at the optimal element spacing at each D.

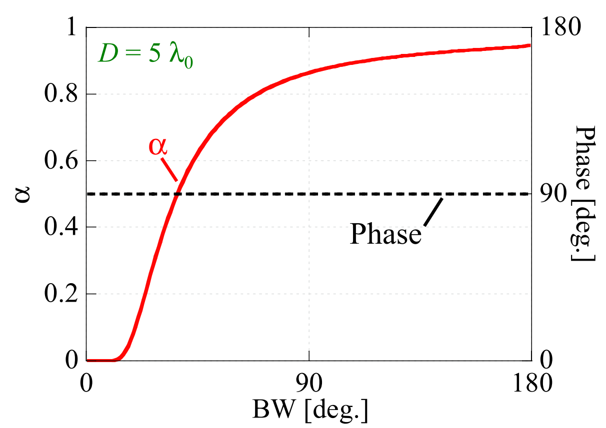

Fig. 9 Weight factor α and phase difference at the optimal element spacing when $D = 5\lambda_0$.

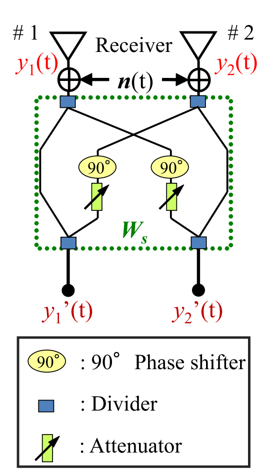

Fig. 10 Proposed analog beamforming circuit when using the directional antenna.

4. Basic Performance of the Simple Decoding Method

To verify the basic performance of the proposed method, the BER and the channel capacity using the proposed method are evaluated.

4.1 Simulation Conditions

In the simulation, the channel matrix, $\boldsymbol{H}_0$, is calculated by the geometrical optics approximation [24]. Although a mutual coupling effect cannot be reflected by using geometrical optics approximation, we have already confirmed that the channel capacity obtained by geometrical optics approximation is almost same with that by Moment of Method analyses which considers the mutual coupling effect between antennas [24]. Hence, we adopted the geometrical optics approximation in this section. The results in which the mutual coupling effect is considered are shown in Sect. 5. The antenna distance, D, is set to be $2\lambda_0$. The modulation scheme is 16 QAM and number of data streams is equal to the number of transmit antennas. One million bits are totally transmitted by the transmit antennas in order to evaluate the BER characteristic which is equal to 10^{-5}. We assume that the weight matrix given in Eq. (9) can be ideally obtained with the analog circuit using the proposed method. The issue of phase errors caused by the phase shifter remains and will be evaluated in future work.

4.2 BER Characteristics

Figure 11 shows the BER versus the array element spacing, d, when a 2×2 MIMO system is considered. *Prop.* in Fig. 11 denotes the proposed simple decoding method, and the results using the proposed method and ZF are plotted in this figure. The SNR per antenna is 20 dB at the optimal element spacing. Although the BER by proposed method is 6×10^{-4} while the BER is less than 10^{-5} by the ZF at the

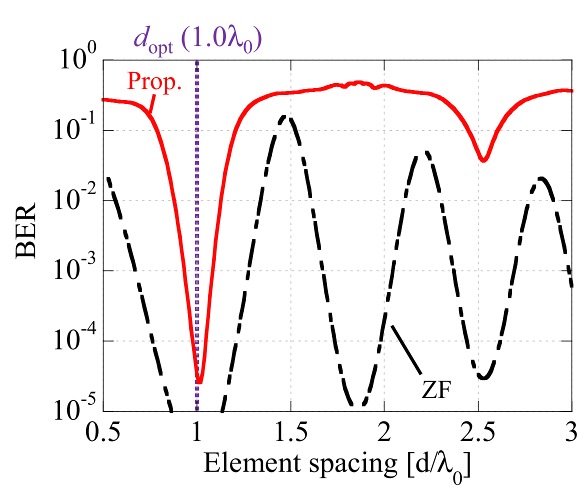

Fig. 11 BER versus element spacing (2×2 MIMO, $D = 2\lambda_0$).

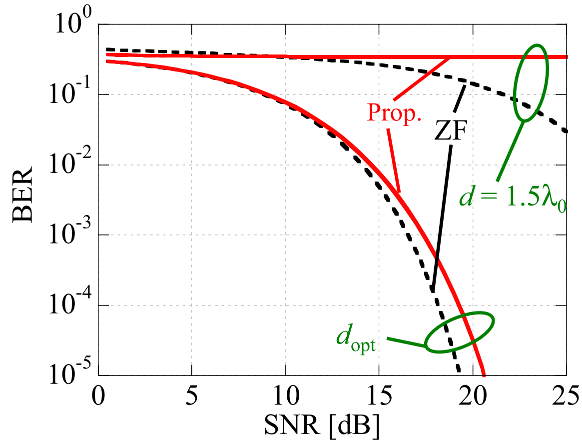

Fig. 12 BER versus SNR (2×2 MIMO, $D = 2\lambda_0$).

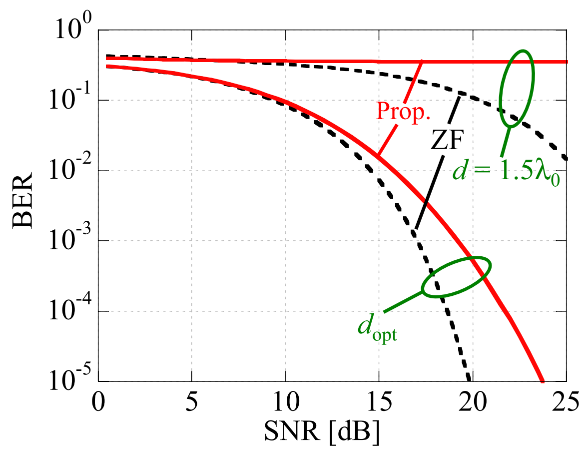

Fig. 13 BER versus SNR (4×4 MIMO, $D = 2\lambda_0$).

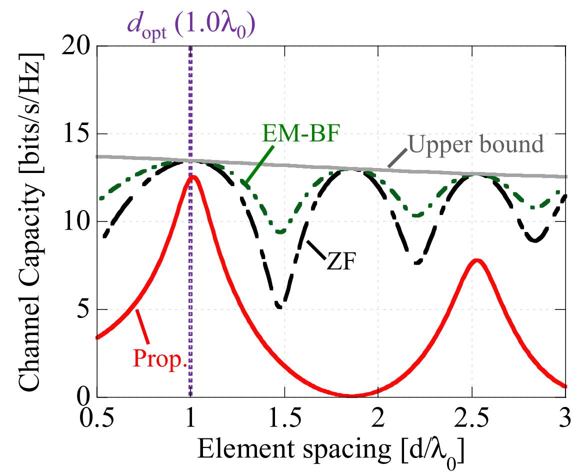

Fig. 14 Channel capacity versus element spacing (2×2 MIMO, $D = 2\lambda_0$).

optimal element spacing ($d = 1.0\lambda_0$), the BER can be actually zero when the error coding scheme is employed. On the other hand, the BER using the proposed method is greatly degraded at all other element spacings except for the optimal element spacing. Hence, it is shown that the use of the optimal element spacing is essential in the proposed circuit for the given the transmit distance.

Figure 12 shows the BER versus the SNR when 2×2 MIMO transmission is employed. The array element spacing, d, is set to be $d_{opt}(= 1.0\lambda_0)$ and $1.5\lambda_0$, respectively, in Fig. 12. The results using the simple decoding method, *Prop.*, and ZF are plotted in this figure. As can be seen in Fig. 12, only 1 dB of degradation exists when the BER$=10^{-3}$ compared to ZF, when using the proposed method with d_{opt}. On the other hand, the BER using the proposed method is not improved versus the SNR, whereas the BER using the ZF is improved at SNRs over 20 dB when d is $1.5\lambda_0$.

Next, we evaluate the effectiveness of the proposed method when 4×4 MIMO is applied. We assume that the weight matrix $\boldsymbol{W}_{s,4\times4}$ given in Eq. (21) can be ideally obtained in the proposed method. Figure 13 shows the BER versus the SNR when 4×4 MIMO with a square antenna arrangement at both the transmitter and receiver is considered. The other simulation conditions are the same as those in Fig. 12. As can be seen in Fig. 13, compared to ZF, 2.5 dB of degradation exists at BER$=10^{-3}$ when using the proposed method with d_{opt}. On the other hand, the BER using the proposed method is not improved versus the SNR when considering that d is $1.5\lambda_0$. Therefore, it is clarified that a simple decoding method is applicable for 4×4 MIMO if we utilize the optimal element spacing.

4.3 Channel Capacity Characteristics

To confirm the validity of our derivation of the channel capacity, the channel capacity versus array element spacing, d, is plotted when 2×2 MIMO is considered. *Prop.* in Fig. 14 denotes the proposed simple decoding method, and the results using the proposed method and ZF are plotted in this figure. The SNR per antenna is 20 dB. As can be seen in Fig. 14, *Prop.* has almost the same performance as ZF and the upper bound [24] at the optimal element spacing. Moreover, because the tendency regarding channel capacity versus d in Fig. 14 is similar to that in Fig. 11, the corresponding values of the *optimal* and *worst* element spacings in each figure are equivalent. Hence, it is clarified that our derivation of the channel capacity is effective for evaluating the upper bound on the transmission performance.

5. Effectiveness of the Proposed Method Using Measured Propagation Channel

To verify the effectiveness of the proposed method in a real propagation environment, the channel matrix is measured when considering the environment in the SR-MIMO transmission.

5.1 Measurement Environment

Figure 15 shows the measurement environment. We conducted the measurement in an anechoic chamber. In order to obtain pure channel responses between the transmit

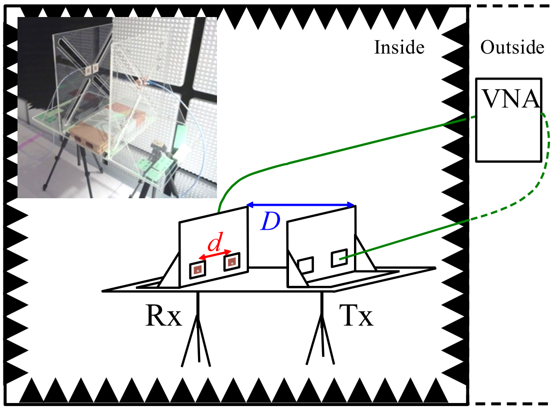

Fig. 15 Measurement environment.

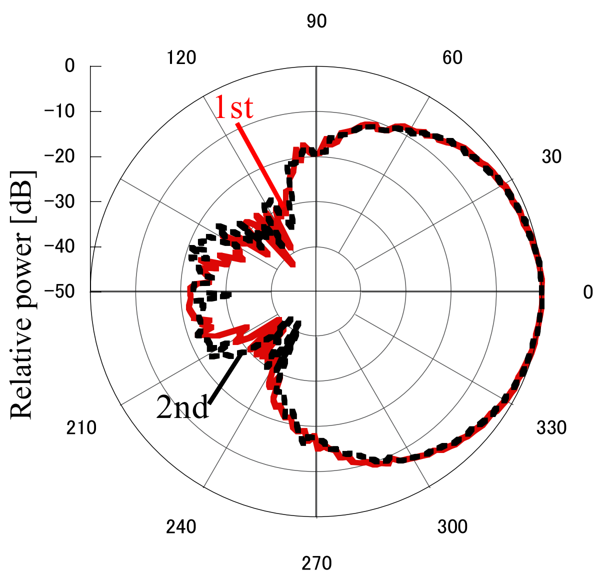

Fig. 16 Radiation patterns of MSA.

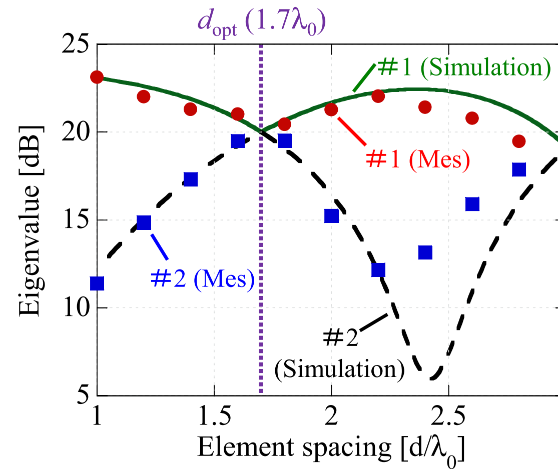

Fig. 17 Eigenvalues versus element spacing (2×2 MIMO, SNR = 20 dB, $D = 5\lambda_0$).

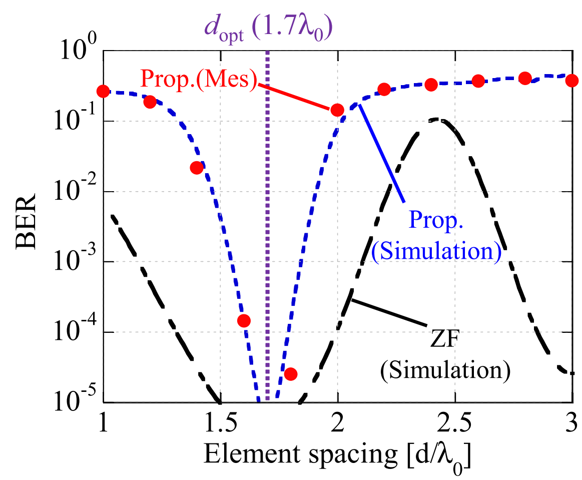

Fig. 18 BER versus element spacing when the measurement channel matrix is considered (2×2 MIMO, $D = 5\lambda_0$).

and received antennas, channel matrix $\boldsymbol{H}_0$ with 2×2 MIMO was obtained by using a vector network analyzer. The center frequency is 5.0 GHz, and the bandwidth is 100 MHz in this measurement. For antenna elements, MSAs are used. The radiation patterns are plotted in Fig. 16. The measured HPBW is approximately 80 degrees. Hence, the HPBW is set to be 80 degrees in the simulation, and the antenna response is approximated by a $\cos^n$ pattern which is shown in 3.3 in the simulation results. The antenna distance, D, is set to be $5\lambda_0$.

5.2 Effectiveness of Proposed Method

Figure 17 shows the 1st and 2nd eigenvalues (λ_1 and λ_2) versus the element spacing. For reference, the simulation result with a $\cos^n$ pattern is plotted in this figure. The SNR is set to be 20 dB when the optimal element spacing is used. As can be seen in Fig. 17, we can observe the existence of the *optimal* element spacing where the ratio of λ_1 and λ_2 is approximately one in the measured results. Moreover, the ratio of the eigenvalues to the element spacing found in the measured results is very similar to that found in the simulation results. Hence, it is clarified that the simulation model is effective for the modeling of an SR-MIMO system when using a directional antenna.

Figure 18 shows the BER versus array element spacing, d, when the measured channel matrix is considered. For the comparison, the results of the proposed method and ZF are plotted in this figure. As can be seen in Fig. 18, the degradation of the BER using the simple decoding method is very small compared to the BER using the proposed method in the simulated results when considering the optimal element spacing. On the other hand, the BER using the proposed method is greatly degraded at element spacings other than the optimal element spacing. Hence, the measurement results show that the usage of the optimal element spacing is essential.

In the previous results, we evaluated the BER and channel capacity at only a single frequency. However, broad-

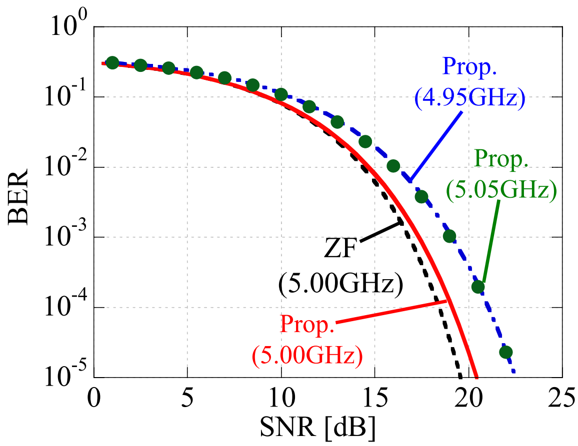

Fig. 19 BER versus SNR when the bandwidth is considered (2×2 MIMO, $D = 5\lambda_0$).

band transmission is essential for future wireless communications. Figure 19 shows the BER versus SNR when the fixed weight given at 5.0 GHz is applied for the weights at 4.95 and 5.05 GHz, respectively. As can be seen in Fig. 19, although a degradation of 1.5 dB exists at BER=10^{-3} when 4.95 and 5.05 GHz are used compared to 5.0 GHz, it is shown that the wideband characteristics can be observed using the proposed simple decoding method if we can prepare the wideband 90-degree phase shifter.

6. Conclusion

In this paper, a novel analog decoding method with only an *analog circuit* is proposed to simplify the decoding method for SR-MIMO transmission. The proposed method does not need any digital signal processing, which is required in conventional MIMO signal decoding. Because the weight matrix found using ZF at the optimal element spacing is expressed as a unitary matrix, it was shown that the weight matrix can be realized by using dividers and 90-degree phase shifters in a 2×2 SR-MIMO system. In this study, the channel capacity using the proposed method is derived to evaluate the limitation on the proposed method. Moreover, it was clarified that simple decoding when using the directional antennas can be configured by using dividers, 90-degree phase shifters, and attenuators.

It was verified that the degradation of the BER using a simple decoding method is very small compared to the BER using ZF when considering the optimal element spacing, d_{opt}. Only 1 dB of SNR degradation exists when BER=10^{-3} compared to ZF, when using the proposed method with d_{opt}. On the other hand, it was shown that the BER using the proposed method is greatly degraded at all other element spacings except the optimal element spacing. Hence, the use of the optimal element spacing is essential for the given transmit distance when employing the proposed method and circuit. We clarified that the *optimal* and *worst* element spacings are the same for the BER and capacity evaluations. Hence, our derivation of the channel capacity is effective for evaluating the upper bound on the transmission performance. Moreover, it was shown that the simple decoding method can be applicable for 4×4 MIMO. Finally, in order to verify the effectiveness of the proposed method in a real propagation environment, the channel matrix was measured when considering the environment during SR-MIMO transmission. It was shown that the simulated and measured results agree well with each other, and the wideband characteristics can be observed with the proposed simple decoding method if we can prepare the wideband 90-degree phase shifter.

Although ideal phase shifters are assumed in this paper, there are phase error on the phase shifter when applying the proposed method. The influence on weight errors on capacity when using the simple decoding scheme is evaluated by a computer simulation [27]. As the future work, the evaluation using actual phase shifters is essential. Moreover, calibration techniques are required to obtain the accurate the channel state information by the proposed method. Hence, actual hardware implementation should be employed for the further development of the proposed method.

In this study, the geometrical optics approximation and cosine pattern were used as the propagation characteristic and antenna pattern in the simulation. Although the simulated and measured results agree with each other from a point of view in BER when the transmit distance is $5\lambda_0$, this assumption may not be applied when considering very near field. As the future work, we should evaluate the limitation regarding the minimum transmit distance that the proposed method can be applicable and a new model in very near field.

Acknowledgments

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